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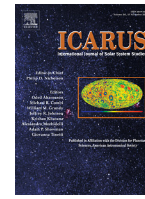

Impact erosion model for gravity-dominated planetesimals

Hidenori Genda[a,*], Tomoaki Fujita[b], Hiroshi Kobayashi[c], Hidekazu Tanaka[d], Ryo Suetsugu[e], Yutaka Abe[b]

[a] Earth-Life Science Institute, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo, 152-8550, Japan
[b] Department of Earth and Planetary Science, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
[c] Department of Physics, Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8602, Japan
[d] Astronomical Institute, Tohoku University, Aramaki, Aoba-ku, Sendai 980-8578, Japan
[e] School of Medicine, University of Occupational and Environmental Health, Iseigaoka, Yahata, Kitakyusyu, 807-8555, Japan

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ABSTRACT

Disruptive collisions have been regarded as an important process for planet formation, while non-disruptive, small-scale collisions (hereafter called erosive collisions) have been underestimated or neglected by many studies. However, recent studies have suggested that erosive collisions are also important to the growth of planets, because they are much more frequent than disruptive collisions. Although the thresholds of the specific impact energy for disruptive collisions ($Q_{RD}{}^*$) have been investigated well, there is no reliable model for erosive collisions. In this study, we systematically carried out impact simulations of gravity-dominated planetesimals for a wide range of specific impact energy (Q_R) from disruptive collisions ($Q_R \sim Q_{RD}{}^*$) to erosive ones ($Q_R << Q_{RD}{}^*$) using the smoothed particle hydrodynamics method. We found that the ejected mass normalized by the total mass (M_{ej}/M_{tot}) depends on the numerical resolution, the target radius (R_{tar}) and the impact velocity (v_{imp}), as well as on Q_R, but that it can be nicely scaled by $Q_{RD}{}^*$ for the parameter ranges investigated ($R_{tar} = 30$–300 km, $v_{imp} = 2$–5 km/s). This means that M_{ej}/M_{tot} depends only on $Q_R/Q_{RD}{}^*$ in these parameter ranges. We confirmed that the collision outcomes for much less erosive collisions ($Q_R < 0.01\ Q_{RD}{}^*$) converge to the results of an impact onto a planar target for various impact angles (θ) and that $M_{ej}/M_{tot} \propto Q_R/Q_{RD}{}^*$ holds. For disruptive collisions ($Q_R \sim Q_{RD}{}^*$), the curvature of the target has a significant effect on M_{ej}/M_{tot}. We also examined the angle-averaged value of M_{ej}/M_{tot} and found that the numerically obtained relation between angle-averaged M_{ej}/M_{tot} and $Q_R/Q_{RD}{}^*$ is very similar to the cases for $\theta = 45°$ impacts. We proposed a new erosion model based on our numerical simulations for future research on planet formation with collisional erosion.

1. Introduction

Collisions are one of the most fundamental processes in planet formation. In each stage of planet formation, many collisions take place continuously, and the impact scale varies from micrometers to the 1000 km scale. For example, accumulation of micrometer dust occurs early in the stage of planetesimal formation (e.g., Weidenschilling, 1980; Wada et al., 2009), the accretion of km-sized planetesimals occurs in the stage of protoplanet formation (e.g., Wetherill and Stewart, 1989; Kokubo and Ida, 1996), and giant impacts of 1000 km protoplanets occur in the last stage of terrestrial planet formation (e.g., Chambers and Wetherill, 1998; Kokubo and Genda, 2010).

If colliding bodies simply merge, collisions promote planet growth. However, collision phenomena are not so simple. For example, in the stage of planetesimal formation, collisions between dust aggregates accelerated by turbulence in a protoplanetary disk can be so destructive that the dust aggregates break into fragments instead of growing (Weidenschilling, 1984; Wada et al., 2008). The stage of protoplanet formation involves a similar problem. Protoplanets become massive, their stirring increases the random velocity of surrounding planetesimals, and collisions between planetesimals become more destructive. As meter-sized fragments resulting from the destructive collisions between planetesimals are removed by rapid radial drift due to gas drag in the protoplanetary disk, the depletion of bodies accreting onto protoplanets can stall protoplanet growth (Inaba et al., 2003; Kenyon and Bromley, 2008; Kobayashi et al., 2010, 2011). Conversely, the radial drift of fragments resulting from destructive collisions can also accelerate protoplanet growth at a pressure maximum in the protoplanetary disk (e.g., Kobayashi et al., 2012; Zhu et al., 2012).

* Corresponding author.
E-mail address: genda@elsi.jp (H. Genda).

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Depending on the impact energy of two colliding objects, the collision outcomes can be divided roughly into two categories: disruptive collision and non-disruptive collision. Disruptive collision, which occurs in high-energy impacts, extensively destroys the colliding bodies. In contrast, non-disruptive collision produces a mass of ejecta that is much smaller than the total mass of the colliding bodies. In the literature on planetary collisions, the specific energy of impact is often used to discuss collisional outcomes. Here, we use the following expression of the specific impact energy from Leinhardt and Stewart (2012):

$$Q_R = \left(\frac{1}{2}M_{tar}V_{tar}^2 + \frac{1}{2}M_{imp}V_{imp}^2\right)/M_{tot} = \left(\frac{1}{2}\mu v_{imp}^2\right)/M_{tot}, \quad (1)$$

where M_{tar} and M_{imp} are the mass of the target and impactor (here $M_{tar} > M_{imp}$, and $M_{tot} = M_{imp} + M_{tar}$), respectively, V_{tar} and V_{imp} are the velocity of the target and impactor in the frame of the center of mass when the two objects contact each other, respectively, μ is the reduced mass $M_{imp}M_{tar}/M_{tot}$, and v_{imp} is the impact velocity ($v_{imp} = V_{imp} - V_{tar}$ for negative V_{tar}). The subscript R in Q_R means reduced mass. Although the classical definition of the specific energy of impact ($Q = 0.5\ M_{imp}\ v_{imp}{}^2\ /\ M_{tot}$) has been used frequently, we use Q_R expressed in Eq. (1). Note that Q_R is identical to Q when the impactor is much smaller than the target ($M_{imp} << M_{tar}$).

The critical specific impact energy ($Q_{RD}{}^*$), which is the specific impact energy required to disperse the target in two or more bodies with the largest body having exactly half the total mass (i.e., $M_{tot}/2$) after the collision, is often used to characterize disruptive collisions (Leinhardt and Stewart, 2012). Disruptive collisions ($Q_R \sim Q_{RD}{}^*$) have been regarded as an important process for planet formation but non-disruptive small-scale collisions ($Q_R << Q_{RD}{}^*$) have been frequently underestimated or neglected (e.g., Inaba et al., 2003; Wyatt, 2008). Here, we call non-disruptive small-scale collisions "erosive collisions," because the mass ejected is much smaller than the total mass. Recent studies (Kobayashi et al., 2010; Kobayashi and Tanaka, 2010) have suggested that erosive collisions are also important to the growth of planets. The reason that these collisions are also important is mainly because erosive collisions are much more frequent than disruptive collisions. Although disruptive collisions ($Q_R \sim Q_{RD}{}^*$) have been investigated extensively (e.g., Benz and Asphaug, 1999; Leinhardt and Stewart, 2012; Jutzi, 2015; Movshovitz et al., 2016), erosive collisions ($Q_R << Q_{RD}{}^*$) have not been investigated well. There is also no reliable scaling model for erosive collisions between planetesimals. There are several reasons why erosive collisions have not been investigated well: (1) very high numerical resolution is needed to numerically resolve a small impactor, (2) erosive collisions had been not regarded as an important process for planet formation, and (3) an extensive parameter search for Q_R is needed for erosive collisions (for example, $Q_R/Q_{RD}{}^* = 0.01 - 1$) compared to disruptive collisions (just around $Q_R/Q_{RD}{}^* = 1$).

In this study, we carried out impact simulations of gravity-dominated planetesimals, using the smoothed particle hydrodynamics (SPH) method. We systematically investigated the dependence of collision outcomes, namely ejected mass on the numerical resolution, target size, impact velocity and impact angle for a wide range of specific impact energy (Q_R) from disruptive collisions ($Q_R \sim Q_{RD}{}^*$) to erosive ones ($Q_R << Q_{RD}{}^*$). Our aim in this study was to investigate the relationship between ejected mass and specific impact energy (Q_R) for various impact parameters and construct a reliable impact erosion model of collisions between gravity-dominated planetesimals for future work on planet formation.

In Section 2, the methods for the numerical code and the initial conditions for collisions are introduced. Section 3 presents the numerical simulation results and investigates the dependence of collision outcomes on the impact parameters. In Section 4, we construct a new erosion model based on our numerical simulations and compare our results with those of some previous studies.

2. Methods

2.1. Numerical code for collisions

To perform impact simulations of planetesimals, we used the SPH method (e.g., Lucy, 1977; Monaghan, 1992), which is a flexible Lagrangian method of solving hydrodynamic equations and has been used widely for impact simulations in planetary science. The SPH method can easily process large deformations and shock waves. Our numerical code is the same as the code used in Genda et al. (2015a,b). It includes self-gravity but does not include material strength. Here, we briefly summarize the code.

The mutual gravity is calculated using the standard Barnes–Hut tree method (Barnes and Hut, 1986; Hernquist and Katz, 1989) on a multicore CPU. The computational cost, which is proportional to $N\log N$, allowed us to deal with a large number of SPH particles. Additionally, we applied the modified terms in the equations of motion and energy proposed by Price and Monaghan (2007) to conserve the energy more effectively. In all of our simulations, the error of the total energy was within 0.1% during impact simulation.

Von Neumann–Richtmyer-type artificial viscosity (Monaghan, 1992) was introduced to capture shock waves. A parameter set of $\alpha = 1.0$ and $\beta = 2.0$ was applied in the artificial viscosity term, because these values are quite appropriate for dealing with the energy partition between kinetic and internal energy during propagation of the shock waves induced by a planetesimal-sized collision (Genda et al., 2015a).

The Tillotson equation of state (EOS) developed by Tillotson (1962), which has been applied widely to date in previous studies including planet- and planetesimal-size collisional simulations (e.g., Benz and Asphaug, 1999; Canup and Asphaug, 2001; Jutzi et al., 2010; Genda et al., 2012; Citron et al., 2015; Hosono et al., 2016; Rosenblatt et al., 2016), was used in our SPH code. The Tillotson EOS contains 10 material parameters, and the pressure is expressed as a function of the density and the specific internal energy, which is convenient for treating fluid dynamics. In this paper, we assumed that the colliding planetesimals are undifferentiated rock, and we used the Tillotson EOS with the parameter sets of basalt referenced in Benz and Asphaug (1999). For planetary sized collisions that involve vaporization of rock, another sophisticated but complicated EOS such as ANEOS (Melosh, 2007) has been often used (e.g., Canup 2004; Ćuk and Stewart, 2012). However, in this paper, we used the Tillotson EOS, because almost all previous studies on planetesimal collisions have used the Tillotson EOS, which allows us to directly compare our results with their results (Benz and Asphaug, 1999; Jutzi et al., 2010; Genda et al., 2015a; Movshovitz et al., 2016).

2.2. Initial conditions for collisions

As shown in Fig. 1, we simulated impacts between two planetesimal-size objects. We considered three sizes of targets with radii of $R_{tar} = 30$, 100, and 300 km. If a planetesimal with $R_{tar} <\sim 100$ km is made up with a monolithic rock, the effects of elastic strength of rock would not be negligible (e.g., Jutzi et al., 2010). However, it is expected that a growing planetesimal is not a monolithic rock, but would be a pile of damaged rocks like a rubble pile, because they have grown through a lot of collisions. In this scenario, neglecting gravity as we have done is reasonable.

In order to investigate the dependence of collision outcomes on the specific impact energy (Q_R), we changed the size of the